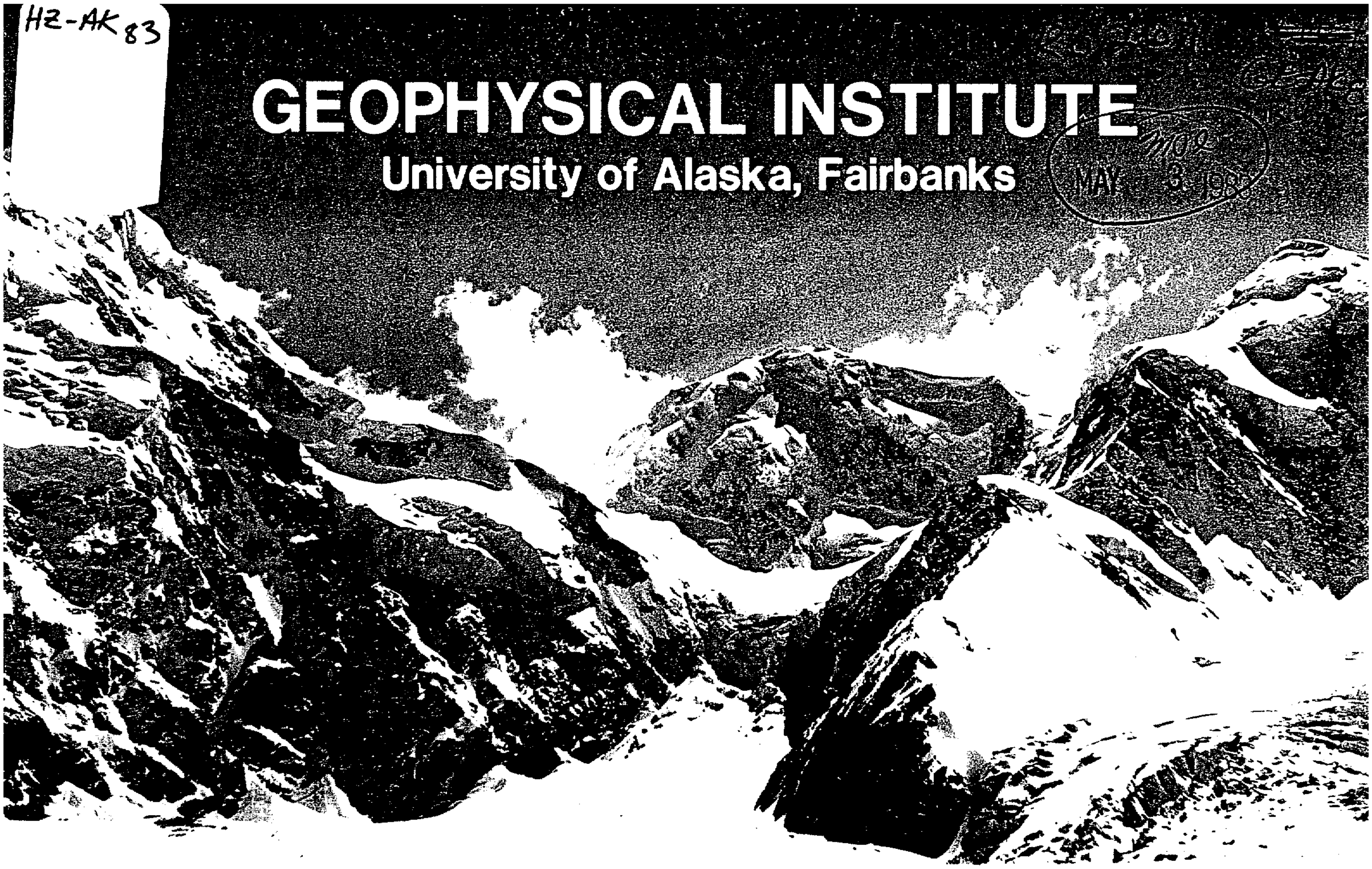

Glacier-Volcano Interactions on Mt. Redoubt, Alaska With Related Flooding Hazards

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ABSTRACT

Mt. Redoubt is a glacier covered, intermittently active volcano on the west side of Cook Inlet, opposite Kenai, Alaska. Its summit is 3100 m above sea level. An unnamed glacier, herein called the North Glacier, flows from the summit crater down to the Drift River, where the glacier terminus forms one wall of the river channel. Glaciological studies began on Mt. Redoubt in 1977 within the summit crater and were extended to the terminus of the North Glacier in 1978. Flow has been measured on this portion of the glacier yearly since 1978. A debris-laden flood, simultaneous with volcanic eruptions in 1966, covered this portion of the glacier with thick debris; this flood extended all the way to Cook Inlet and made it necessary to evacuate a seismic crew from near the mouth of the Drift River. The evacuation site is now the home of an oil tanker terminal. Volcanically triggered floods still constitute a potential hazard for the terminal, but a second, more immediate flooding hazard is associated with the North Glacier. Advance of its terminus would dam the Drift River. A pulse of rapidly thickening and accelerating ice is moving down the North Glacier at speeds about five times faster than the normal ice flow speeds measured on this glacier. The pulse, in many respects a small glacier surge, may be a complex result of several causes including volcanic heating, catastrophic ice loss during the 1966 eruptive action, and changes in ablation due to insulating volcanic debris. The arrival of the pulse at the terminus may cause advance sufficient to dam the Drift River. If the Drift River does become dammed by advance of the North Glacier, it would form an unstable glacier dammed lake. When this lake breaks through, over or under its dam of glacier ice, it will produce flooding in the Drift River.

Acknowledgements

This research has been made possible by assistance from many people; it is a pleasure to acknowledge their support. Our initial studies at the summits of Mts. Redoubt and Iliamna were begun in 1977 with aid from the U.S. Army NWTC at Ft. Greely, Alaska through arrangements made by Lt. Col. Richard Bauchspies, Commandant. Logistical support in the field has been provided by the U.S. Geological Survey, the Alaska Division of Geological and Geophysical Surveys (ADGGS), and by the Cook Inlet Pipe Line Company, The company provided air transport by fixed wing and helicopter aircraft and special aid at Drift River Camp where the hospitality has been superb; special thanks go to Messers Absher, Greene, Jones, Lewis and the entire crew at Drift River terminal. From 1977 through 1979 we had sustained support and encouragement from the Bureau of Land Management through an interagency agreement with the National Oceanic and Atmospheric Administration, under which a multiyear program responding to the needs of petroleum development of the Alaskan Continental Shelf is managed by the OCSEAP office (Contract no. 03-5-022-55, Task 2).

Some of the work has been supported by State of Alaska Funds through the Geophysical Institute.

Finally we pay special tribute to the late Peter MacKeith. He was a delightful friend and colleague in both the field and office; we miss him. His enthusiasm for the problems on Mt. Redoubt was contagious. We regret that his tragic, untimely death prevented him from seeing the exciting developments with us.

Glacier-Volcano Interactions on Mt. Redoubt, Alaska with Related Flooding Hazards

INTRODUCTION

Mt. Redoubt is a glacier-clad volcano 3108 meters (10,197 feet) high, located on the west side of Cook Inlet directly across from Kenai and 175 kilometers west-southwest of Anchorage. It has erupted at least five times since 1778. During a period of volcanic activity in 1966, flood waters from its summit crater washed down the Drift River and flooded the area where a large oil tanker terminal is located today.* In addition to the possible recurrence of this type of flooding, there is a possibility that the Drift River could be dammed by the unnamed glacier flowing north from the summit crater of Mt. Redoubt. This glacier, herein called the North Glacier, is undergoing changes in which the ice is thickening and flowing with increasing speed. Should this event cause the glacier terminus to advance, the Drift River could be dammed, resulting in the formation of an unstable, glacier-dammed lake which could break out in a catastrophic flood. The subject of this report is the North Glacier on Mt. Redoubt.

LOCATION AND GEOGRAPHY

Mt. Redoubt, which is shaped like a truncated cone, forms an extensive highland between the Drift River on the north and the Crescent River on the south (see Figure 1). Both rivers, which originate from the glaciers on Mt. Redoubt, flow east into Cook Inlet. In general, the area is sparsely populated. However, an oil tanker terminal is at the mouth of Drift River; it consists of a number of large oil storage tanks, operating buildings and living quarters, plus an airstrip and an off-shore loading

*Jökulhlaups is the Icelandic term for glacier outburst floods, sometimes associated with volcanism; this term is now used for these catastrophic events worldwide.

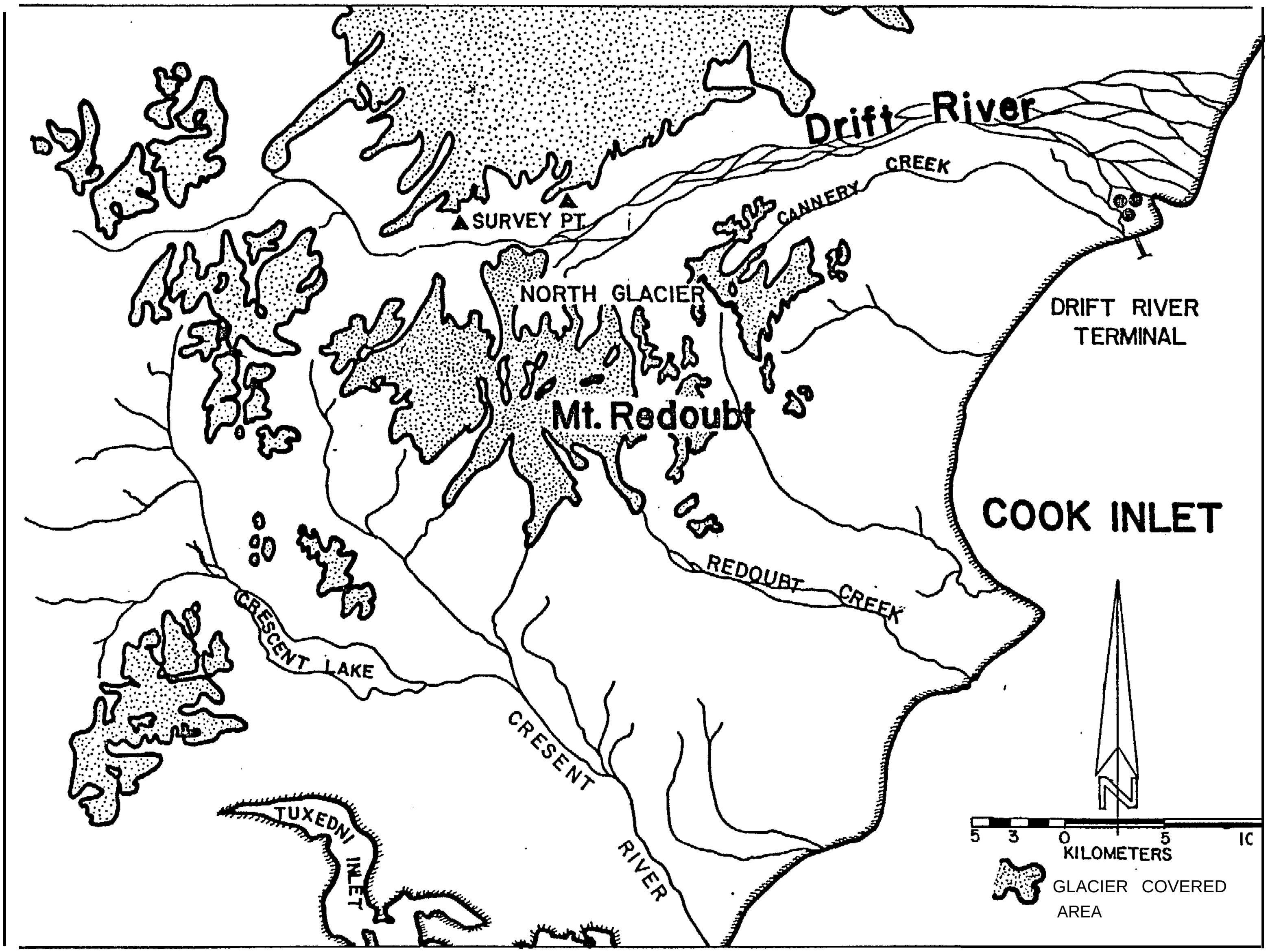

Figure 1: Location Map showing Mt. Redoubt, North Glacier and Drift River Oil Tanker Terminal

platform. The lowlands and river bottoms are heavily vegetated with fir and cottonwood trees with a thick understory of willow and alder. Above 300 meters the terrain is generally covered by ice or year-round snow.

Description of North Glacier

A crater at the summit of Mt. Redoubt forms the source of the North Glacier which can be divided into five sections (see Figure 2). The ice-filled crater of Mt. Redoubt has an ice surface elevation of 2590 meters. Accumulation in the crater is augmented by continual avalanching from the steep sides of the crater bowl. Ice from this summit crater spills into the upper canyon section of the North Glacier over a threshold whose characteristics are not known. Small fumaroles are present along the edge of the gap through which the ice flows.

The upper canyon section of the North Glacier follows a narrow gorge, five kilometers long and 400 meters to 700 meters wide. The gradient of this portion of the glacier is 15° to 30°, though just below the summit crater there is a very steep ice-fall. Rock falls, avalanching and tributary ice streams contribute to the glacier's mass in this section. Crevassing is severe and in one place a rib of bedrock seems to split the surface of the glacier.

To the east of the upper valley section lies the east basin, with a mean elevation of 1800 meters. It is an extensive accumulation area that may occupy an older, breached crater of Mt. Redoubt. Ice from this basin cascades onto the upper canyon in a series of ice falls over steep rock cliffs which in places are over 100 meters high.

Below the confluence of ice from the east basin and ice of the upper canyon, the North Glacier flows through the lower canyon which

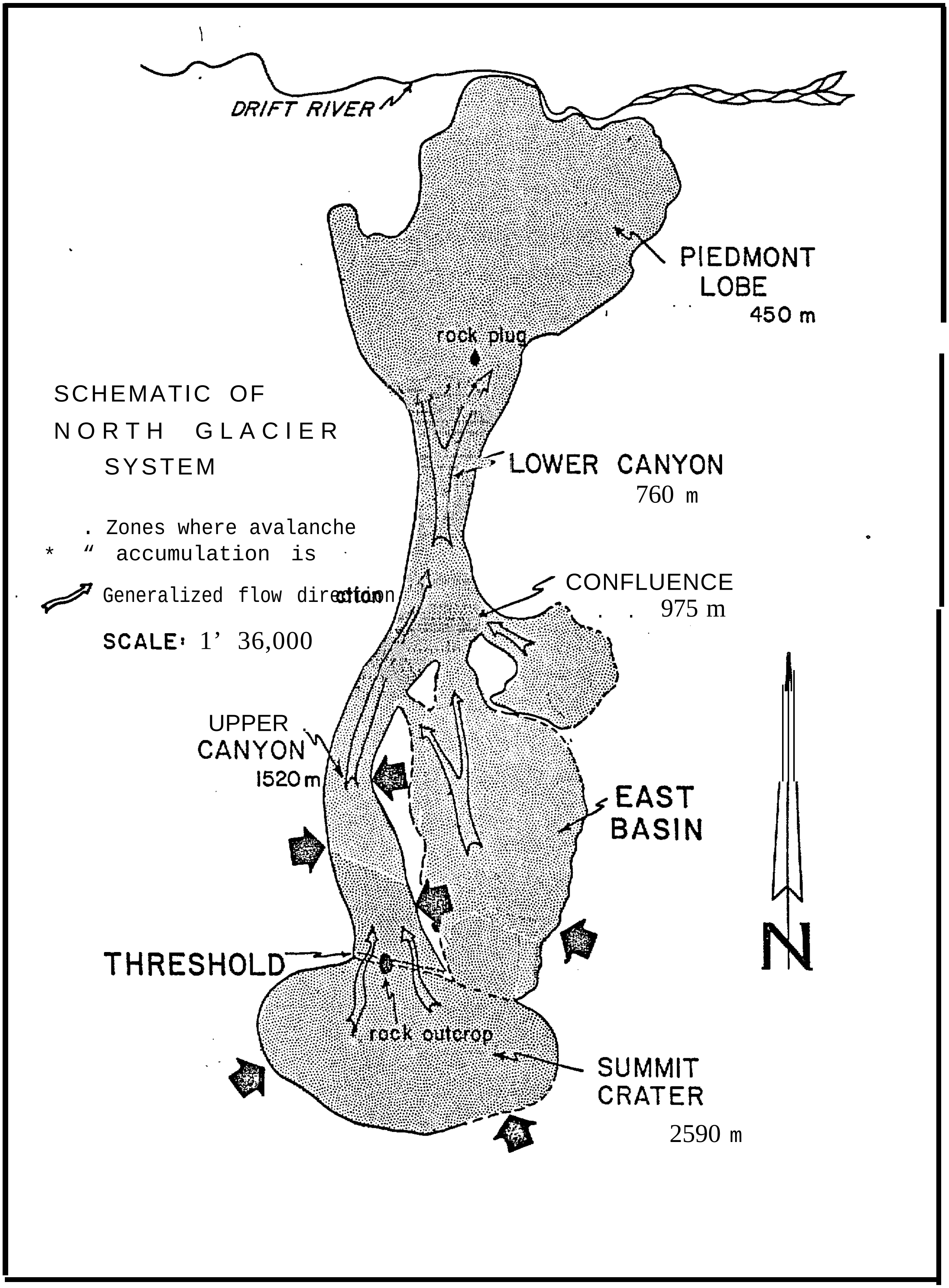

Figure 2: Schematic of the North Glacier system showing average elevations

is 2.6 kilometers long and 500 meters wide, is heavily crevassed, and, as in the upper sections, has sidewalls from which avalanching adds significantly to the glaciers mass.

The lowest section is a broad, piedmont glacier lobe which begins six kilometers from the summit crater and four kilometers from Drift River where the glacier exits from the confines of the narrow lower valley. The Drift River runs due east here in a wide valley, into which the North Glacier spreads to form its piedmont lobe. A rock plug projects through the piedmont lobe just below its exit into the valley bottom. This plug seems to divide the flow of the glacier. Below the plug, the glacier is heavily mantled with debris of various origins in a striking pattern of flat terraces and ridges, crescent-shaped in plan view and convex down-glacier. The ridges are spaced 200 to 300 meters between crests, each ridge consisting of broken volcanic rock. (The pattern is suggestive of ogives.) The flat terraces between the ridges are filled with unconsolidated sandy volcanic material deposited during the 1966 jökulhlaups. The far west portion of the lobe is covered with thick brush. The terminus of the lobe forms the south wall of a narrow gorge through which the Drift River flows; the opposite wall is the base of a steep, 1000 meter high ridge.

Description of Drift River

The Drift River flows in braided stream channels along its two-kilometer wide valley floor, except where it passes the North Glacier; here its channel is less than 50 meters wide, and the constraining walls rise steeply from the water's edge. At its mouth, the river has built a broad delta where it flows into Cook Inlet; the channel now in use runs just north of the tanker terminal installation.

BRIEF HISTORY OF GLACIOLOGICAL STUDIES ON MT. REDOUBT

1977. The first year's field work, in 1977, concentrated on the summit crater (see Table 1). In July, 1977, a network of survey points and air photo control points were established at the 2500 meter level on Mt. Redoubt. A snowpit was dug in the crater and a core taken to a depth of ten meters. This showed accumulation was greater than ten meters of snow with a water equivalent of at least 4.8 meters. Later in the summer, vertical aerial photographs were taken of the crater and North Glacier. From these and similar photos taken in 1954 by the USGS, a set of comparative photogrammetric maps on a scale of 1:3,000 was prepared.*

1978. During the field season of 1978 an array of 15 movement stakes was established on the piedmont lobe of the North Glacier (see Figure 3). Two baseline survey stations and two pre-marked control points were established in preparation for aerial photogrammetry of the glacier terminus region; aerial photos were taken later in the summer. Because of the heavy debris cover, the movement stakes were stuck upright in dirt and secured by rock cairns built around their bases. The debris cover provided insulation which protected the ice from ablation. Ablation was measured at a stake which was drilled into the ice horizontally at the terminus and another stake placed vertically, three kilometers from the terminus. A second visit in September of 1978 indicated that ablation was greater than four meters per year in both locations. During this second visit all movement stakes were resurveyed with the exception of stakes D-1 and D-2, which had melted out. Additionally, the morphology and geology of the Drift River flood channel and its modification during

*The aerial photography and photogrammetric mapping was contracted through North Pacific Aerial Survey Inc., Anchorage, Alaska.

SUMMARY OF GLACIOLOGICAL WORK ON MT. REDOUBT

YEAR	DATE	FIELD WORK	PHOTOGRAPHY	PRODUCTS
1977	July	1. Installed survey network for summit region. 2. Snowpit and core to 10 meters.	Vertical photos of North Glacier and crater. July 1, 1977.	Map 1:3000 for 1954, 1977 of crater.
1978	12 July	1. Established movement stakes on North Glacier. 2. Established survey control network for North Glacier. 3. Studied geology of Drift River flood channels. and 1966 jökulhlaup debris.	Vertical photos of North Glacier and crater. July 31, 1978.	
	14 Sept.	1. Resurveyed movement stakes on North Glacier. 2. Studied geology of Drift River flood channels.		
1979	8 Aug.	1. Resurveyed movement stakes on North Glacier	Vertical photos of North Glacier and crater. Aug. 22, 1979.	
1980	28 Aug.	1. Resurveyed movement stakes on North Glacier.		
1981	26 Aug.	1. Resurveyed movement stakes on North Glacier. 2. Examined lacustrine sediments near North Glacier.		
1982	28 July	1. Resurveyed movement stakes on North Glacier.		Presentation at Pacific Northwest AGU meeting.
			Vertical photos of North Glacier and crater. Sept. 23, 1982.	Report to Cook Inlet Pipeline and ADDGS.
	15 Oct.	1. Resurveyed movement stakes on North Glacier. 2. Examined protective dikes around Drift River terminal.		

TABLE 1

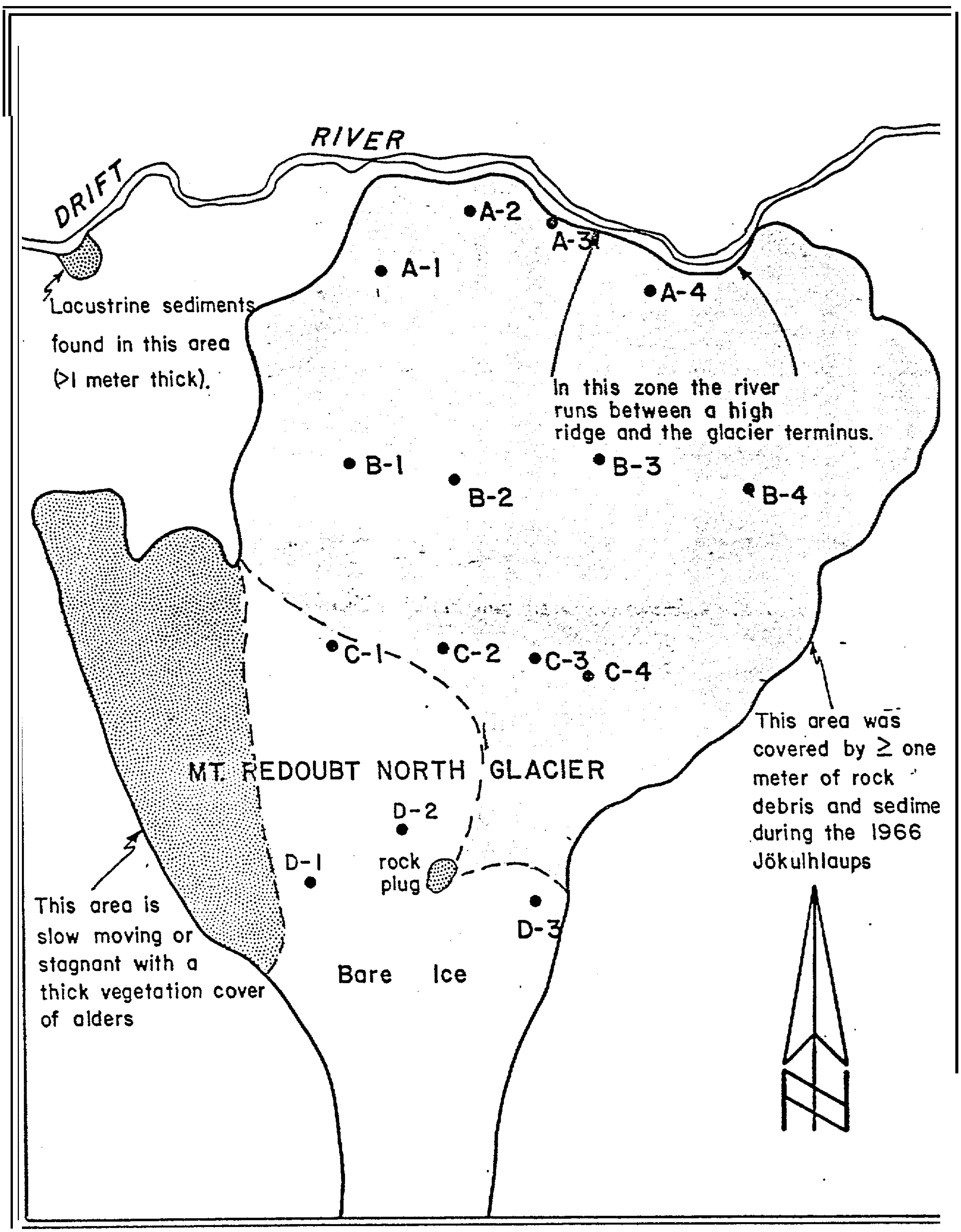

Figure 3: Piedmont Lobe of North Glacier of Mt. Redoubt showing movement stake, array and location of lacustrine sediments

the 1966 jökulhlaups was studied.

1979. Field work in 1979 was primarily geologic, however, all stakes were resurveyed, and in September, another set of vertical aerial photographs was obtained.

1980. In August, 1980, all movement stakes which could be found were resurveyed. Stakes D-3 and C-1 could not be found and were presumed to have fallen over during the winter. No aerial photographs were taken.

1981. In late August of 1981 all movement stakes were again resurveyed. Stake B-2, B-3 and C-2 could not be found, so new stakes were placed in approximately the position of the original stakes. Luckily, stake C-1, lost after 1979, was re-discovered intact and resurveyed in 1981. Again, no aerial photos were obtained, though a helicopter reconnaissance of the summit crater and fumarole field was conducted,

1982. Field work for 1982 consisted of obtaining survey measurements in late July and again in mid-October. All existing stakes were found. An attempt to place tetrahedral markers for obtaining movement data in the lower canyon section of the glacier failed due to poor weather. Aerial photos were obtained in late September of 1982. Data analyzed after the July 1982 field work indicated that it would be prudent to warn the operators of the Drift River terminal and the Alaska State Geologist that a significant flooding hazard might exist on the Drift River. Preliminary reports were sent to these two agencies.

VOLCANIC HISTORY OF MT. REDOUBT

Before discussing jökulhlaups which have come from glaciers on Mt. Redoubt or the possibility of damming the Drift River by the North Glacier, it is appropriate to review the known volcanic history, since it is clear that these volcanic events have profoundly affected the glacier dynamics of the North Glacier. The historic record extends back to 1778, when Mt. Redoubt exhibited some activity (type unknown). In 1819, Mt. Redoubt was reported to be “smoking”, indicating either steam and/or ash eruptions. The next known eruption was in 1902. Large explosive events, extrusion of lava and the ejection of pyroclastic material, spreading hundreds of kilometers from the volcano, accompanied this period of activity which lasted at least two months. In 1933 Mt. Redoubt again showed activity, but only in the form of steam clouds over the crater.

The most recent eruptive cycle was from 1965 to 1968. Activity during 1965 was predominantly quiescent steam emissions. On January 24, 1966 voluminous steam and ash eruptions occurred. Activity continued through January 26th, at which time a jökulhlaups emerged from a point just below the summit crater on the North Glacier and traveled down the Drift River. This flood, heavily ladened with debris, removed large amounts of ice from the North Glacier (see below), covered the piedmont lobe with thick sediment, caused the break-up of the winter ice on the Drift River, and required the evacuation of a seismic crew from the site of the present oil tanker terminal. The height of the flood waters at the terminal site have been estimated at over one meter, and described as carrying huge chunks of ice.

Eruptive activity for Mt. Redoubt remained high through February, 1966 and another large jökulhlaups occurred on February 4th. This period of intense activity, consisting of explosive vapor columns, with ejection of ash and scoria and accompanying jokulhlaups, ended on February 20th, 1966. After a quiescent period, renewed activity began in

January 1967, with phreatic explosions and some pyroclastic ash ejects. After another quiescent period, eruptive activity began in December, 1967 and lasted until February, 1968. Again, this activity consisted primarily of phreatic explosions with some pyroclastic ejects. The mountain has been quiet since February, 1968.(see Table 2).

FLOOD HAZARDS ON MT. REDOUBT

Mt. Redoubt poses a dual flooding hazard. Historic and geologic information indicates that there is a flooding hazard associated with the volcanic heating of the mountain. Jökulhlaups originate when a pool of meltwater breaks loose from somewhere in a glacier; jökulhlaups occurred during the 1965-1968 period of activity. A second flooding hazard is associated with the possible damming of the Drift River by a small advance of the North Glacier. If the river became dammed in this way a temporary lake would form. Such glacier-dammed lakes generally drain catastrophically when they find a path through or under the ice dam. The geologic record indicates that such lakes have formed. The presence of the tanker terminal at the mouth of the Drift River makes the consequences of either type of flood serious to human activity. Each flooding hazard will be examined separately below.

Flooding Associated with Volcanic Activity

The volcanic events of 1965-1968 were accompanied by major floods which occurred on January 26, 1966 and again on February 4, 1966 (Post and Mayo, 1971; Riehle, et al., 1981). Numerous minor floods occurred all through February and March, 1966, (John Finch, Mobil Oil Co., personal communication), generally occurring some six hours after noticeable

SUMMARY OF HISTORIC VOLCANIC EVENTS - MT. REDOUBT*

YEAR	DURATION	ERUPTIVE PRODUCTS	SOURCE
1778	?	Active - unknown.	Captain James Cook, as reported by Beaglehole (1967
1819	?	Steam and/or ash.	Baron von Wrangell, as reported by Grewingk, 1870
1902	Jan.-Feb.	Explosion with steam and heavy ash up to 100 km distance.	The Alaskan (Sitka), March 22,29, 1902. Daily Alaskan Dispatch (Juneau) March 22, 1902.
1933	May 22-23(?)	Steam and (?) minor ash.	Anchorage Daily Times May 23, 1933 Fairbanks News-Miner May 25, 1933
1965	Jan.29-Feb.4	New fissure around vent with steam.	Fairbanks News-Miner Jan.29,30, Feb.1,2,3,4, 1965
1966	Jan.24-Feb.20	Eruptive column, probably of ash, steam and scoria Jökulhlaups	Nature, No. 5045, July 9, 1966, p. 163- Wilson, Nichparenko and Forbes.
1967	Jan.	Eruptive column probably of steam and ash.	Journal of Geophysical Research, 74, 18, Aug. 20, 1969, Wilson and Forbes.
1967-1968	Dec.6-Apr.28	Eruptive column, with steam and ash.	Journal of Geophysical Research, 74, 18, Aug. 20,, 969, Wilson and Forbes.

*Based, in part, on research done by Aimee J. Panuska and Harriet Small, 1978.

eruptions of the volcano. Highest water levels were in excess of one meter at the terminal site.

Source Area.

The probable source for these jökulhlaups is the summit crater. One hypothesis is that a subglacial reservoir forms under the crater ice by volcanic heating. At a critical water depth, H_c, the ice is floated off of a rock threshold by the buoyant force of the underlying water which pours out; when the ice reseals against the rock threshold, the process is set to repeat (see Figure 4a). Another hypothesis is that ponded water may be released through rock fissures opened during stages of eruptions.

Crater Configuration.

The summit crater could possibly contain ponded water. The ice in the crater forms a fairly level surface and spills out through two exits on either side of a rock plug or dome. The exits are approximately equal in elevation. It is likely a rock threshold is located here (see Figure 4b), although the subglacial topography is not known.

Flood Channels.

Though the source of the flood water is not clear, the flood channels through which it flowed can be identified readily on oblique and vertical aerial photographs (see Figure 5). Just below the summit crater, flood waters in 1966 gouged a deep trough in the icefall. This trough, estimated at over 100 meters wide, was continuous until well below the lower valley section, where the flood waters spread out over the piedmont lobe. Entire sections of ice in the upper valley portion of the glacier were scoured down to bedrock, indicating the removal of an enormous amount

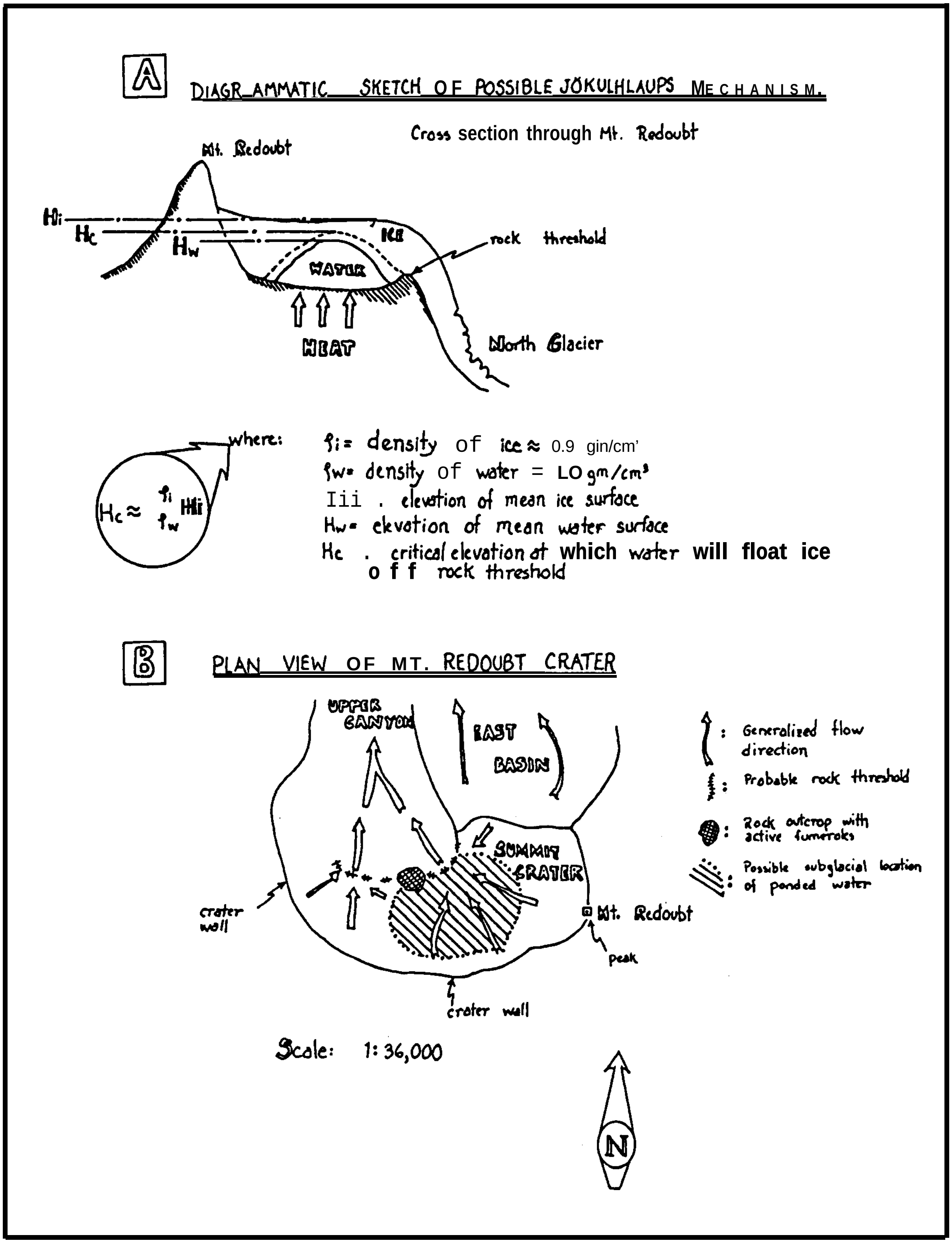

Figure 4a: Possible Mt. Redoubt crater configuration with critical levels indicated for jökulhaups mechanisms

Figure 4b: Plan view of Mt. Redoubt Crater showing ice flow directions

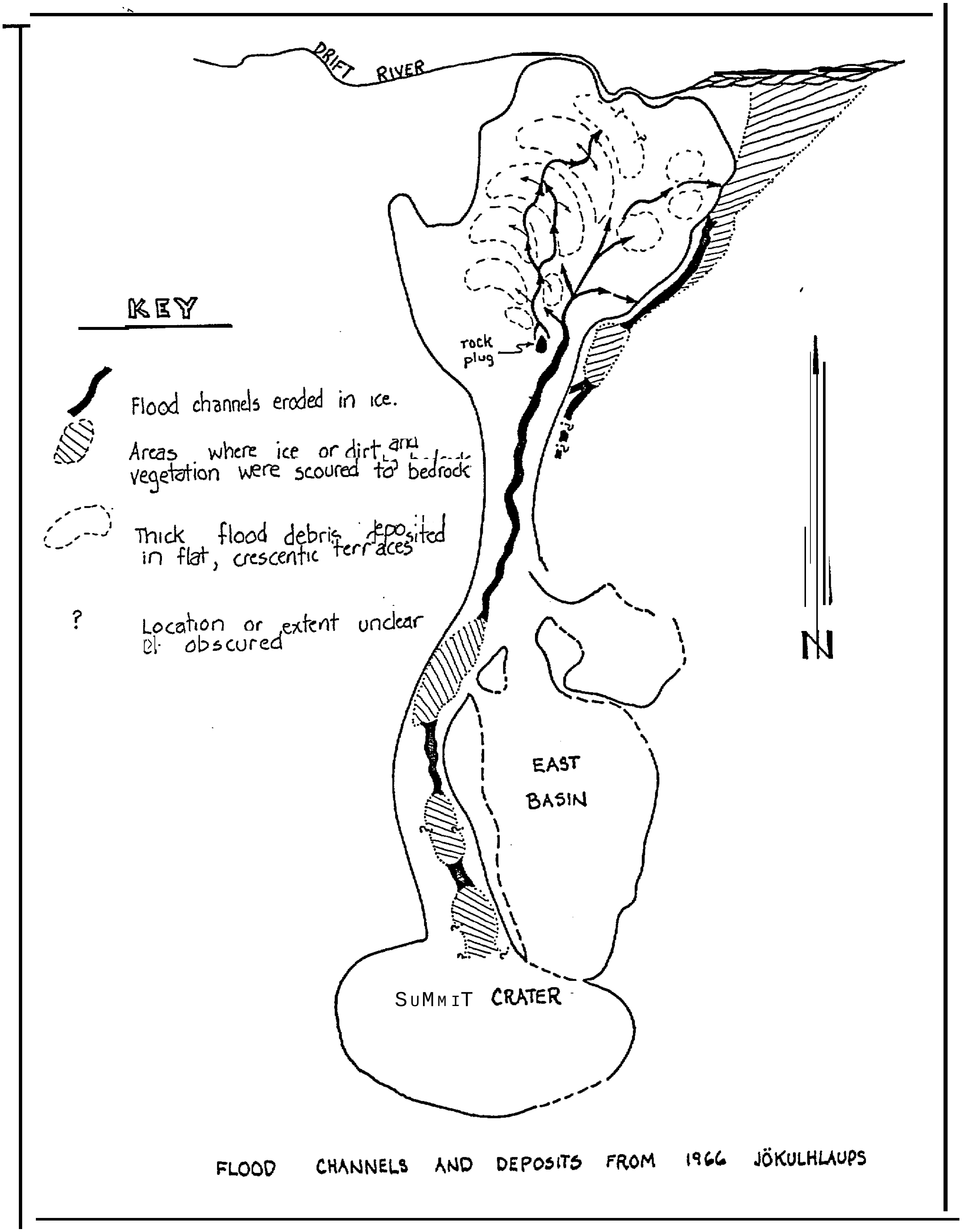

Figure 5: 1966 Flood Channels and deposits on North Glacier, Mt. Redoubt

of ice, a fact which may have profound implications for the present day behavior of the North Glacier. Areas on the eastern margin of the glacier were denuded of vegetation, and newly eroded and washed bedrock indicates that the jokulhlaups discharged a large volume of water. Some of this water may have run subglacially in the upper valley section and emerged at the rock plug to join surface waters in spreading out over the piedmont lobe. The depth and breadth of the flood channel cut in the glacier ice and the presence of multiple channels are consistent with the enormous volume of water involved in a jōkulhlaups. Once the water entered the Drift River valley, the numerous empty braided channels easily handled the flow, but flood waters spread widely over the low-land near the mouth of the river, preferentially following old sloughs and channels. The absence of vegetation over much of the floor of the Drift River valley suggests that this flooding has been a recurrent phenomena over the recent geologic past.

Flood Deposits.

Pyroclastic and fluvial deposits cover the North Glacier lobe. These deposits fill the troughs between crescentic ridges of volcanic rock moraine (see Figure 5). The terrace-like deposits in the troughs were not present in 1964 but show up in 1966 aerial photographs, suggesting strongly that the material was deposited by the floods of 1966. The glacier surface topography prior to 1966 permitted the debris-laden water to form terraces as it moved into the troughs between crescentic ridges.

The material in the troughs is composed of coarse to medium sand and volcanic ash. In places it is over two meters thick and, in 1966, it covered nearly 80% of the piedmont lobe. Where undisturbed, the material is an excellent insulator and severely reduces the melt loss of underlying ice; this is important when considering the mass balance and dynamics of the North Glacier (Driedger, 1981).

Two types of collapse features exist in the trough-filling material. First, kettle holes, often water-filled, are common. Since it is clear from eye-witness accounts of the floods, and from the amount of ice removed from the upper valley glacier, that the flood waters carried large blocks of ice, it is reasonable to assume that some of this ice was washed into the troughs along with the sand and sediment. If these blocks were thinly covered they could melt and form kettle holes. Other collapse features are gashes in the terraces, perpendicular to the crescent-shaped ridges. The gashes are crevasses in the glacier ice showing through the overlying sediment. These gashes can be seen propagating farther and farther down-glacier in aerial photos taken in successive years since 1977. They represent the surface response of the glacier to the passage of a pulse of thickening, accelerating ice. It is important to note that the increased crevassing exposes more ice to ablation and needs to be considered in the overall dynamics of the North Glacier.

Flood Potential of Present-day System.

Since Mt. Redoubt remains active, though quiescent, the possibility of jökulhlaups remains. Investigation of possible ponded water in the summit crater now is critical to an estimation of the potential hazard. Radio-echo sounding to determine the sub-glacial topography of the crater would be necessary to explain and quantify the jökulhlaups.

Flooding Associated with River Damming

The North Glacier forms the steep, south embankment of the Drift River for over a distance of 1.5 kilometers; a small advance of the glacier will dam the river. The north bank is a thousand meter high ridge, which in places forms a cliff at the water's edge. In many places the channel is no more than 20 meters wide, as measured from 1982 aerial photographs. Over the past five years the terminus position has been constant, indicating that ice ablation has balanced ice advance.

The North Glacier has dammed the Drift River in the past as evidenced by lacustrine sediments over one meter thick, found just upstream of the North Glacier (see Figure 3). The extent of the old lake is not known. Considering the topography of the Drift River valley upstream of the North Glacier, rough calculations indicate that a 30 meter thick dam would produce a lake with a volume of 3.2 x 10^7 cubic meters. A sixty meter thick dam would produce a lake of 3.97 x 108 cubic meters. Either case, both of which are reasonable, would produce a sizeable flood when the ice dam failed.

The critical factor controlling whether the river will be dammed is the behavior of the North Glacier terminus. The behavior of a glacier terminus is complex, yet it is clear from data extending back to 1977 that a large flux of ice mass is moving out into the piedmont lobe of the North Glacier. This event makes it more probable that there will be a terminus advance and consequent glacier damming of the Drift River.

Dynamics of the North Glacier

Accumulation.

Measurements in the summit crater showed accumulation in excess of 10 meters of snow (4.8 meters water equivalent) during the 1976-1977 accumulation year. This appears to be a reasonable figure when compared with values for Wolverine Glacier on the Kenai Peninsula and the Capps Glacier on Mt. Spurr (Larry Mayo, personal communication, 1982). Undoubtedly, the amount of accumulation is highly variable from year to year, and is greatly modified by orographic and local topographic sheltering effects.

Assuming a precipitation gradient of 0.30 meters of water equivalent per 100 meters of altitude, as has been found valid for the south side of the Alaska Range (Doug Johnson, personal communication, 1982), we can estimate the accumulation at various altitudes on Mt. Redoubt. From this gradient and the approximate accumulation at the summit crater of 5 meters/year, we find the following:

Elevation in Meters	Accumulation in Meters H20 eqv./year
2600	5
1800	2.6
1520	1.8

The above elevations are mean elevations for the summit crater area, east basin area and upper canyon area, respectively. This constitutes, in general, Mt. Redoubt's accumulation area. Multiplying the accumulation times the surface area of each section gives:

Summit Crater (2.2×10^6 m2) (5.0)

East Basin ($3.8 \times 10^6 m^2$) (2.6) ≈ Total 2.56×10^7 m3 of water equivalent

Upper Canyon ($3.4 \times 10^6 m^2$) (1.8)

This order of magnitude calculation gives the ice volume added yearly to the North Glacier system as being: ($1 m^3$ ice/0.9 m3 water) ($2.56 \times 10^7 m^3$ water eqv.) = 2.8×10^7 m3 ice or, roughly 3×10^7 m3 of ice per year.

Flux.

If the glacier surface over this area is assumed to be in equilibrium, then the yearly increase in water equivalent must be balanced by an equal flux of ice down the glacier toward the ablation area. The flux would be approximately $3 \times 10^7 m^3 H_2O$ eqv./year. This amount must pass through the equilibrium line yearly. The equilibrium line for the North Glacier is located approximately mid-way up the lower canyon section of the glacier. Below this line there must be a net loss of ice which just balances the flux of ice, if the glacier is to maintain equilibrium.

Ablation

Ablation in the lower valley section and piedmont lobe of the North Glacier is in excess of four meters a year for exposed ice. Along the steep face of the terminus above the Drift River, ablation was 4.4 meters over two months in 1977, which, if extended to a total melt season of 3 1/2 months gives approximately a total of eight meters of melt during the year. At the terminus this measurement was made in the vertical ice wall, thus it is also the amount that the terminus would retreat if the ice were not moving forward. As noted earlier, where debris cover is thick, ablation rates drop effectively to zero.

A rough value of the quantity of ice melted annually can be calculated using the above approximate value for annual ablation of eight meters/year and multiplying this by the area of the piedmont lobe and lower valley sections. This gives an annual ice loss of:

$$(5.16 \times 10^6 \text{ m}^3) \times (8\text{m}) = 4 \times 10^7 \text{ m}^3 \text{ ice/yr}$$

assuming no ice is insulated by debris. This value is very close to the annual accumulation over the North Glacier as calculated above.

Consider now the effect of covering half of the ablation area with insulating debris. To be conservative assume that the insulation is only 75% effective (i.e. only a meter of melt yearly). The annual ice loss now would be:

$$(0.5)\ (5.16 \times 10^6 \text{ m}^2) \times (\text{E? m}) \approx 2.1 \times 10^7 \text{ m}^3 \text{ H}_2\text{O eq/yr}$$

$$+\ (0.5)\ (5.16 \times 10^6 \text{ m}^2) \times (0.25)\ (8 \text{ m}) \approx 0.5 \times 10^7 \text{ m}^3 \text{ li}_2\text{0 eq/yr}$$

$$\text{TOTAL} \quad 2.6 \times 10^7 \text{ m}^3 \text{ H}_2\text{0 eq/yr}$$

Subtracting this from the total accumulation of 3 x 10^7 m^3 ice/yr gives 0.4 x 10^7 m3 ice/yr. The effect of this would be that 0.4 x 107 m3 of ice would accumulate annually in the North Glacier system. Since the insulating debris was deposited in 1966, the system has been accumulating this surplus for almost 17 years. This gives a total of 6.8 x 107 m3 of ice, which corresponds to an overall thickening of the entire ablation area of about 13 meters to date, which in fact, is close to what has been observed on the piedmont lobe.

The figures are crude, but do indicate, in order of magnitude, that decreases in ablation due to insulating debris alone can account for a radical thickening of the North Glacier as is presently occurring.

Horizontal Motion.

The horizontal component of ice motion in the piedmont lobe varies from 190 meters per year where it exits the lower valley section (D-line of stakes, see Figure 6} to about 4 meters per year at the terminus (A-line of stakes). These data were obtained by annual triangulation surveys of an array of 15 stakes arranged in four lines labeled A, B, C and D, each row progressively farther up-glacier.

The velocity field of the piedmont lobe is complicated because it has varied progressively over time. In most cases, individual stake velocities have increased yearly since the initial measurements in 1977. This acceleration has proceeded sequentially, with the D-line accelerating first and the A-line showing acceleration five years later. This progressive acceleration is clear when examining each line of stakes through time, as is done below.

A-line: These stakes located along the terminus above the river showed little variation in horizontal velocity until 1982. Prior to this they were generally flowing towards the river at velocities of two to four meters per year, which seemed to be in balance with the local ablation. In July of 1982 a slight increase in velocity was noted at all stakes, with stakes A-3 and A-4 on the east side of the glacier showing the most pronounced acceleration. By October of 1982 the horizontal velocity of the A-line stakes had in-all cases become three or four times the average velocity of the preceding four years (see Figure 7).

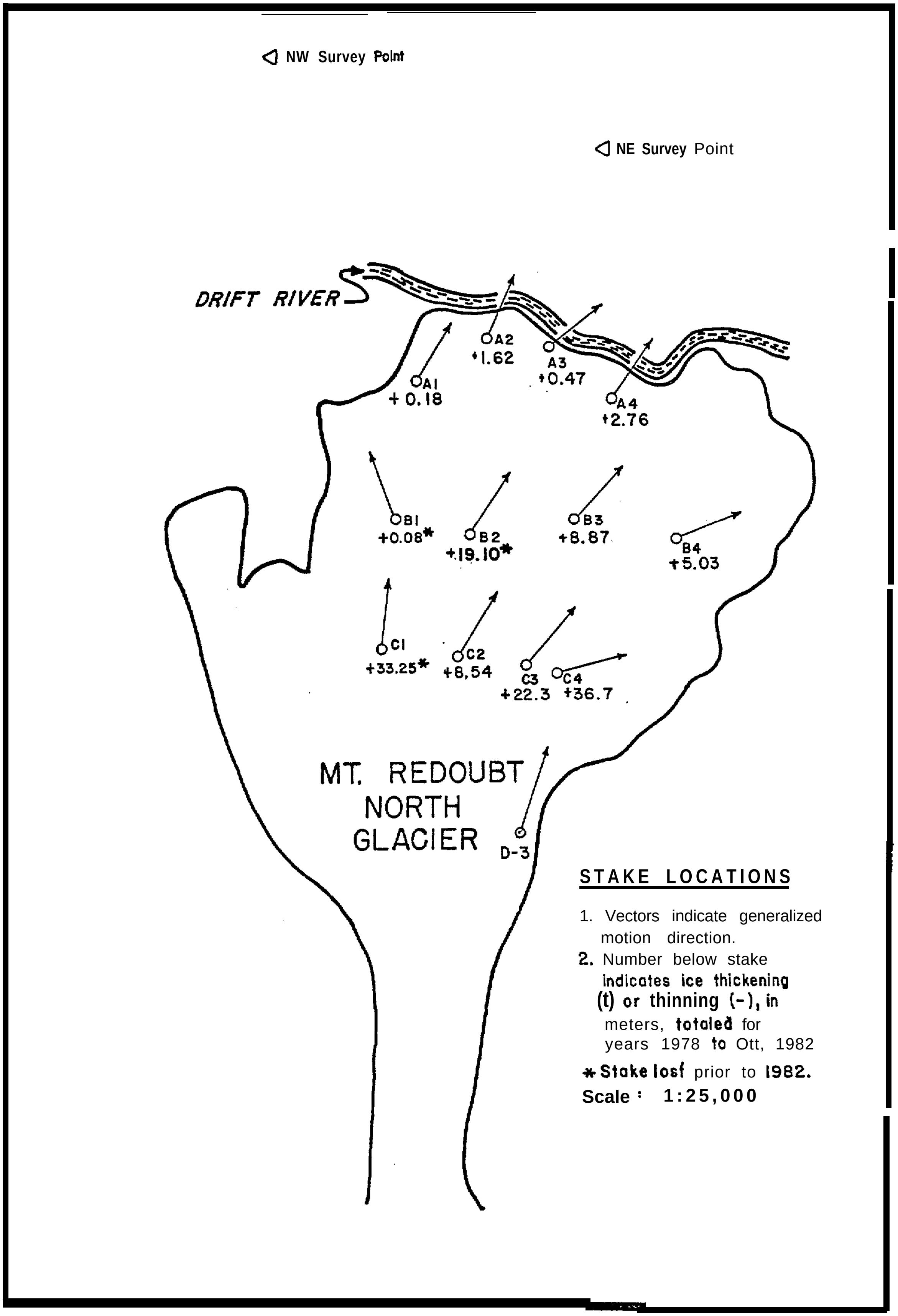

Figure 6: Mt. Redoubt North Glacier movement stakes showing mean ice flow direction and total thickening, 1977-1982

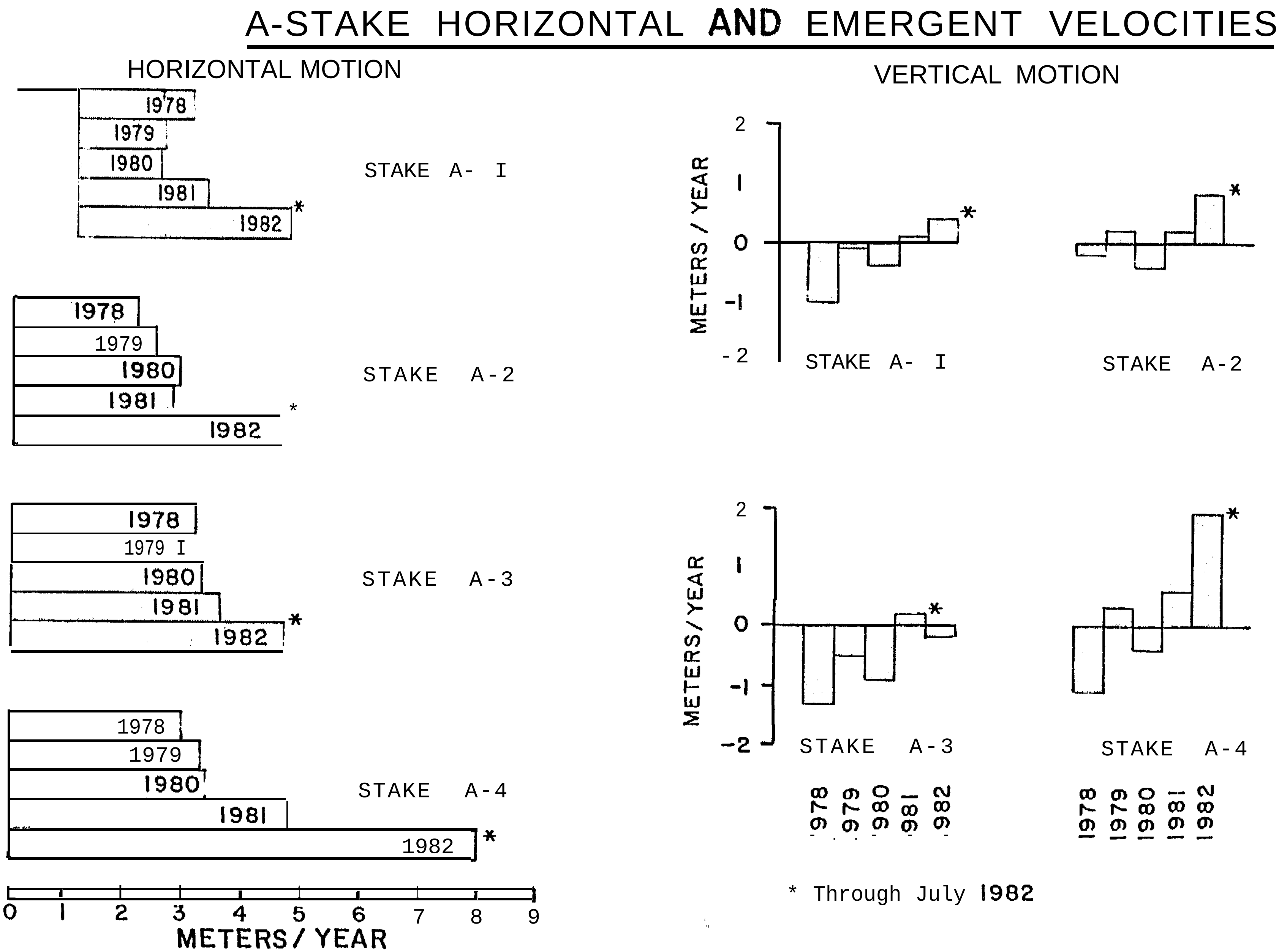

Figure 7: Mt. Redoubt- A-stake horizontal and vertical(emergent) velocities

B-line: These stakes, located approximately 1.4 kilometers from the terminus, showed velocities on the order of 2 to 4 meters per year, until 1981 at which time they showed an abrupt increase to velocities of 12 to 40 meters per year. This marked acceleration continued between July and October, 1982 at which time the velocities ranged from 25 to 70 meters per year, a twelve to twentyfold increase over the velocities of 1978-1981. In particular, stakes B-2 and B-3 in the central and eastern portion of the glacier showed the most notable increases (see Figure 8).

C-line: These stakes, located approximately 2.3 kilometers from the terminus, have shown continuously accelerating 'velocities since 1978. In 1978, stake C-1, on the far western side of the piedmont lobe, was already moving over sixty meters per year. Stakes C-2 and C-3 were much slower, at 16 and 8 meters per year, respectively, while stake C-4 was moving 3 meters per year.

In 1981, stakes C-3 and C-4 showed dramatic acceleration to velocities of over 100 meters per year. (Stake C-2 was lost in that year, so it is not known if it also showed acceleration, but it most probably did). By July of 1982, stakes C-2 (replaced after being lost), C-3 and C-4 had reached maximum horizontal velocities of 153 m/yr, 145 m/yr, and 128 m/yr respectively. This was nearly 50 times the 1978-1980 velocities. These horizontal velocities dropped slightly between July and October of 1982, but still remained well over 100 meters/year.

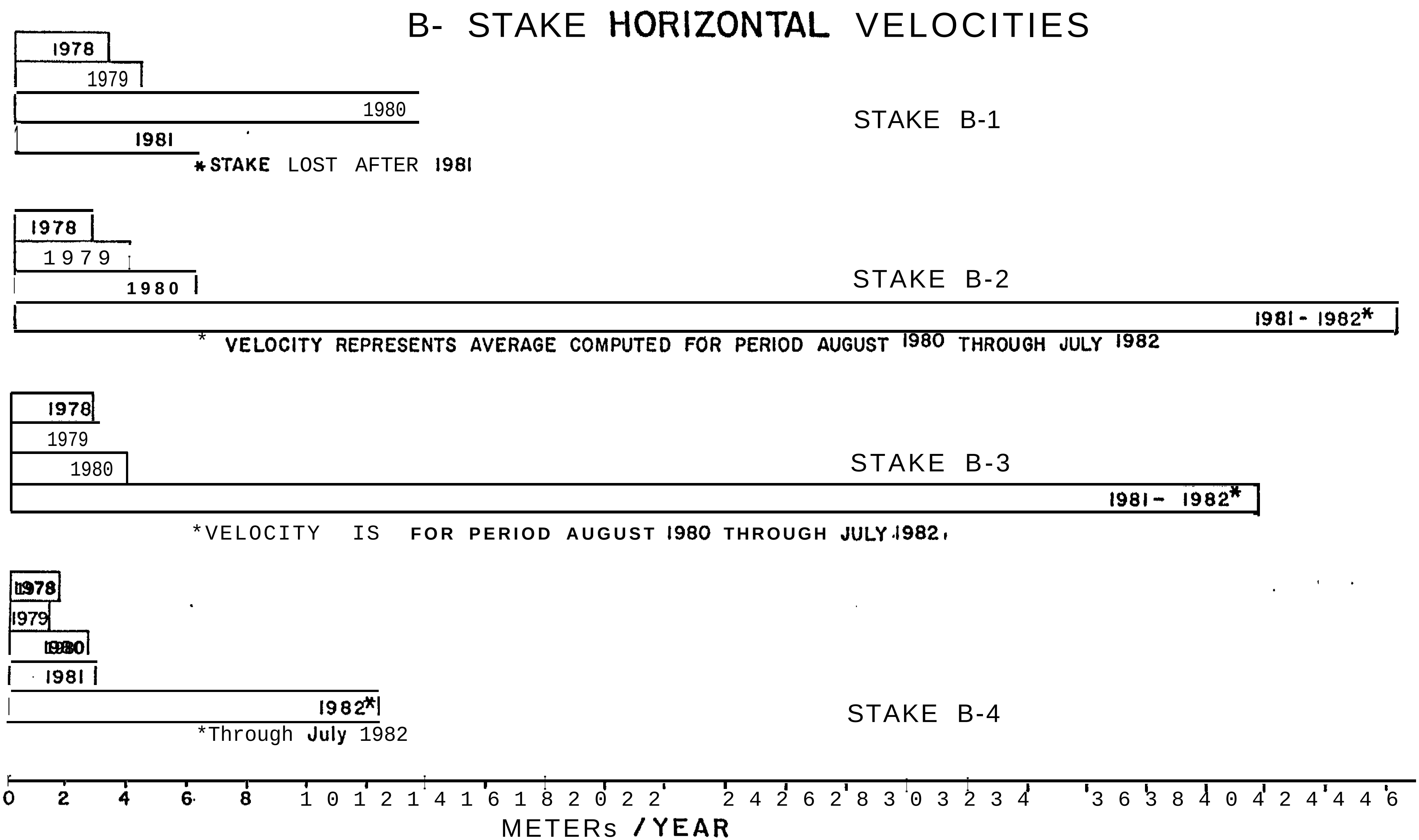

Figure 8: Mt. Redoubt - B-stake horizontal velocities

The C-line is located about 0.6 kilometers down glacier from the rock plug which divides the flow of glacier. This may account for the variation in velocity across the C-line (see Figure 9).

D-line: These stakes, located approximately 2.7 kilometers from the glacier terminus, were lost after the 1978 season, but gave high average ice motion velocities of 190 meters per year. Due to the extremely crevassed nature of the glacier in this location and the high ablation rates, no attempt was made to re-establish the D-line after 1978. It seems likely that the horizontal ice motion in the position of the D-line of stakes had already accelerated prior to 1978.

Vertical Motion.

Changes in the elevation of the stakes were calculated using vertical angles measured from the base line stations. These measurements were corrected for curvature and refraction. They were then reduced to emergent velocities, which are simply the rate of change of elevation, corrected for downslope movement of the stakes.* Errors inherent in the surveying

*Elevations are calculated to the top of each stake (considered fixed with respect to the glacier) using the average of two independent vertical angles (doubled). A standard correction of (6.755×10^{-8}) x (horizontal distance)^2 is applied to the elevation. This accounts for refraction and earth curvature. Accuracy is ± 10 cm at a distance of 3 km. The surface slope of the glacier is taken from the USGS 1:63,360 topographic map (1954) and may be considerably in error in places. (± 2-4°). Emergent velocity is calculated from

$$V_E = (\Delta Z - h\tan\alpha)\left(\frac{365.25}{\Delta t}\right)$$

where V_E = emergent velocity (m/yr)
ΔZ = measured change in elevation of stake between observations
h = horizontal distance to stake
α = glacier slope (the negative sign denotes downslope angles)
Δt = days since last observation

C-' STAKE HORIZONTAL VELOCITIES

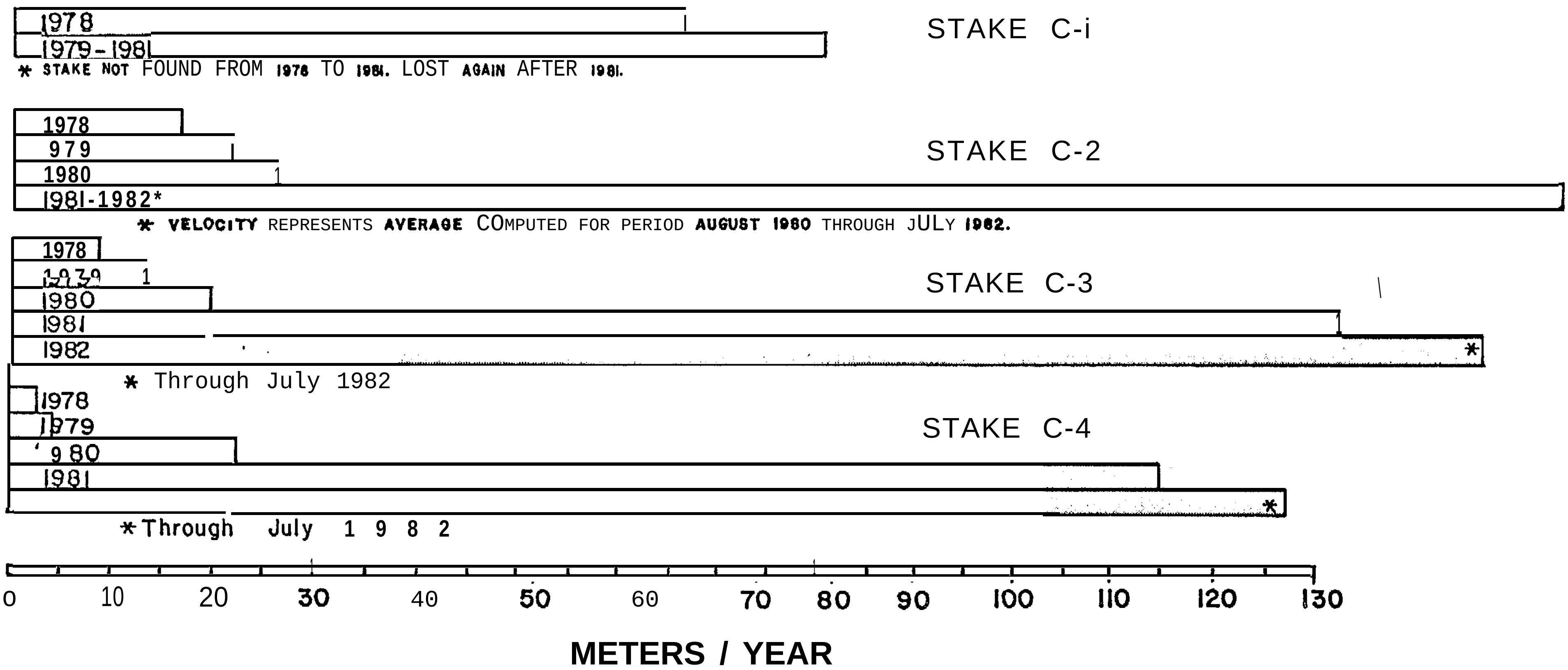

Figure 9: Mt. Redoubt - C-stake horizontal velocities

and ambiguity in glacier surface slope measurements mean that values of the emergent velocity of less than 0.5 meters per year are not significant and basically indicate that vertical motion is essentially zero.

For all stakes, since 1977, there has been a general change from neither thickening nor thinning to a marked and progressive thickening. This change has been synchronous with an acceleration of horizontal velocity at most stakes, though in a number of cases, thickening has preceeded the increase in horizontal motion. Thickening rates of up to 26 meters per year have been observed, with total thickening at some stakes exceeding 30 meters, and the present total thickening shown for each stake on Figure 7.

A-line: Prior to 1980, the stakes of the A-line showed little vertical movement, with the exception of slight thinning at stake A-3. This is interpreted to mean that ablation was negligible at all stakes except A-3, where debris cover may have been thinner and/or less insulating. Stake A-4 showed definite thickening in August of 1981, but it was not until July of 1982 that stakes A-1 and A-2 also showed thickening. This trend continued to accelerate with thickening rates (emergent velocity) reaching nearly five meters per year at A-2. A-3 is beginning to show thickening, but lags behind the others, perhaps due to the up-glacier influence of the rock plug dividing the ice flow (see Figure 7).

B-line: These stakes have behaved similarly to the A-line of stakes, showing thickening as early as 1981, but showing marked thickening in July, 1982 with rapid increases by October of 1982 to rates as high as 11 meters per year for stake B-3 (see Figure 10).

B- STAKE EMERGENT VELOCITIES

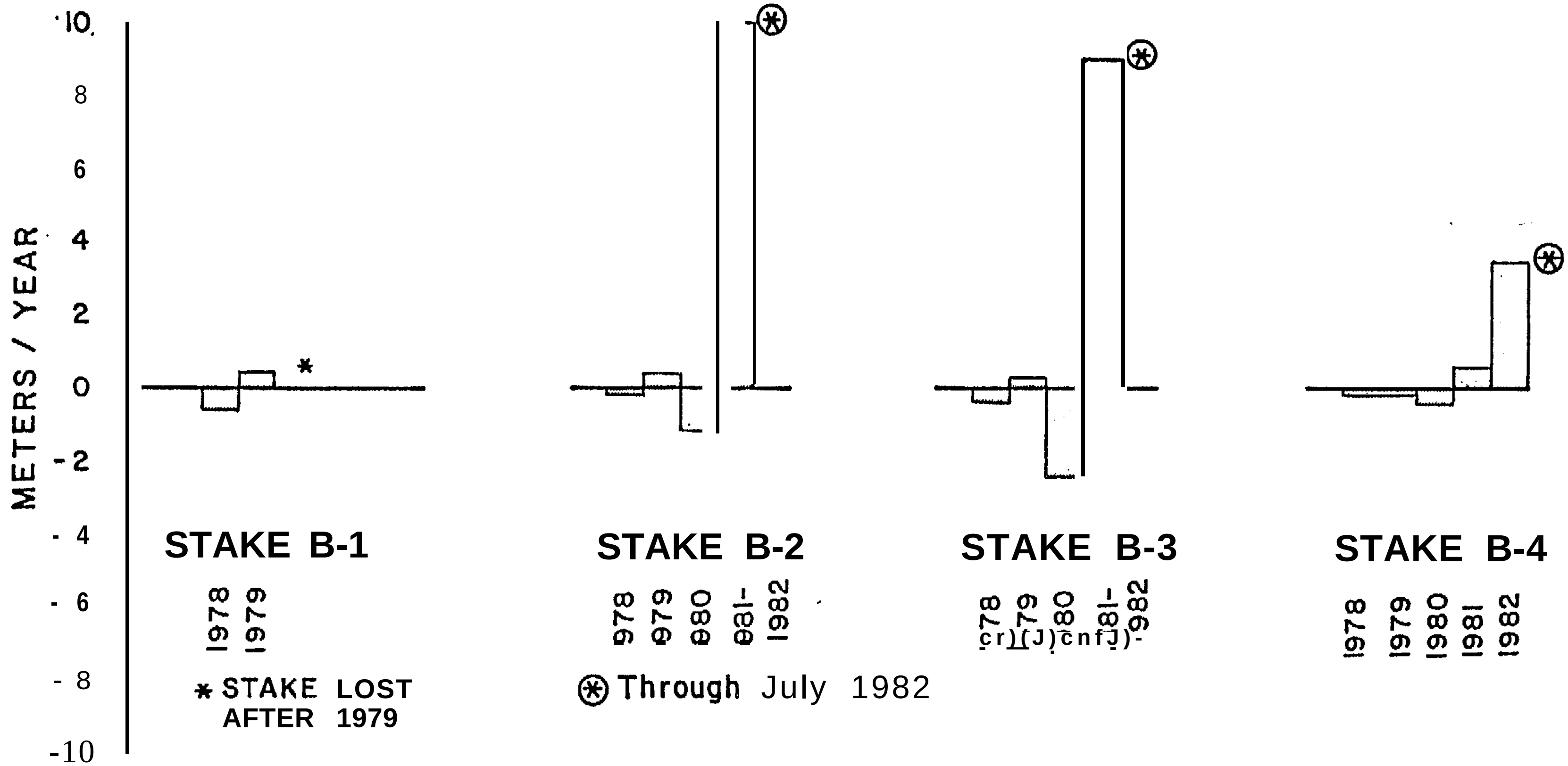

Figure 10: Mt. Redoubt - B-stake emergent velocities

C-line: These stakes showed extremely rapid thickening which peaked in August of 1981, approximately a year earlier than the peak of horizontal velocities at the same location. In 1981 the emergent velocity reached an extreme of 26 meters per year for stake C-4. Stake C-1, previously noted to have shown horizontal acceleration as early as 1978, also had a peak emergent velocity of 22 meters per year the same year and has dropped off since then. Stakes C-2, C-3 and C-4 are still showing marked thickening rates but have dropped off considerably from their 1981 highs (see Figure 11).

D-line: No data on vertical motion are available.

Glacier Surface Changes.

The pulse of horizontally and vertically accelerating ice moving down the North Glacier severely breaks up the glacier surface into gaping, radial, splaying and longitudinal crevasses. Vertical aerial photographs clearly show the propagation of the pulse and allow it to be mapped* (Figure 13). As the crevasses open, they disrupt and destroy the insulating debris cover on the piedmont lobe.

The wave causing the pulse, as mapped from the down-glacier edge of progressive crevassing, has two distinct lobes divided by the rock plug

*At this point it is necessary to clarify the difference betwen the pulse, glacier ice motion and movement stake motion. Survey data gives us stake motion, averaged over time. We assume the stakes are fixed to the glacier, and therefore represent the ice motion at that point. The pulse, however, is not as clearly defined. We only know of its existence by a) the progressive crevassing of the glacier surface through time and b) the progressive acceleration of stakes down glacier. The pulse, a motion event occurring In time, is most likely caused by a wave-like feature traveling down the glacier. As this “wave” passes, it alters the conditions governing glacier flow; it has a shape, amplitude and propagation velocity. The term pulse is used herein to indicate the sequence of events occuring on the North Glacier.

C- STAKE EMERGENT VELOCITIES

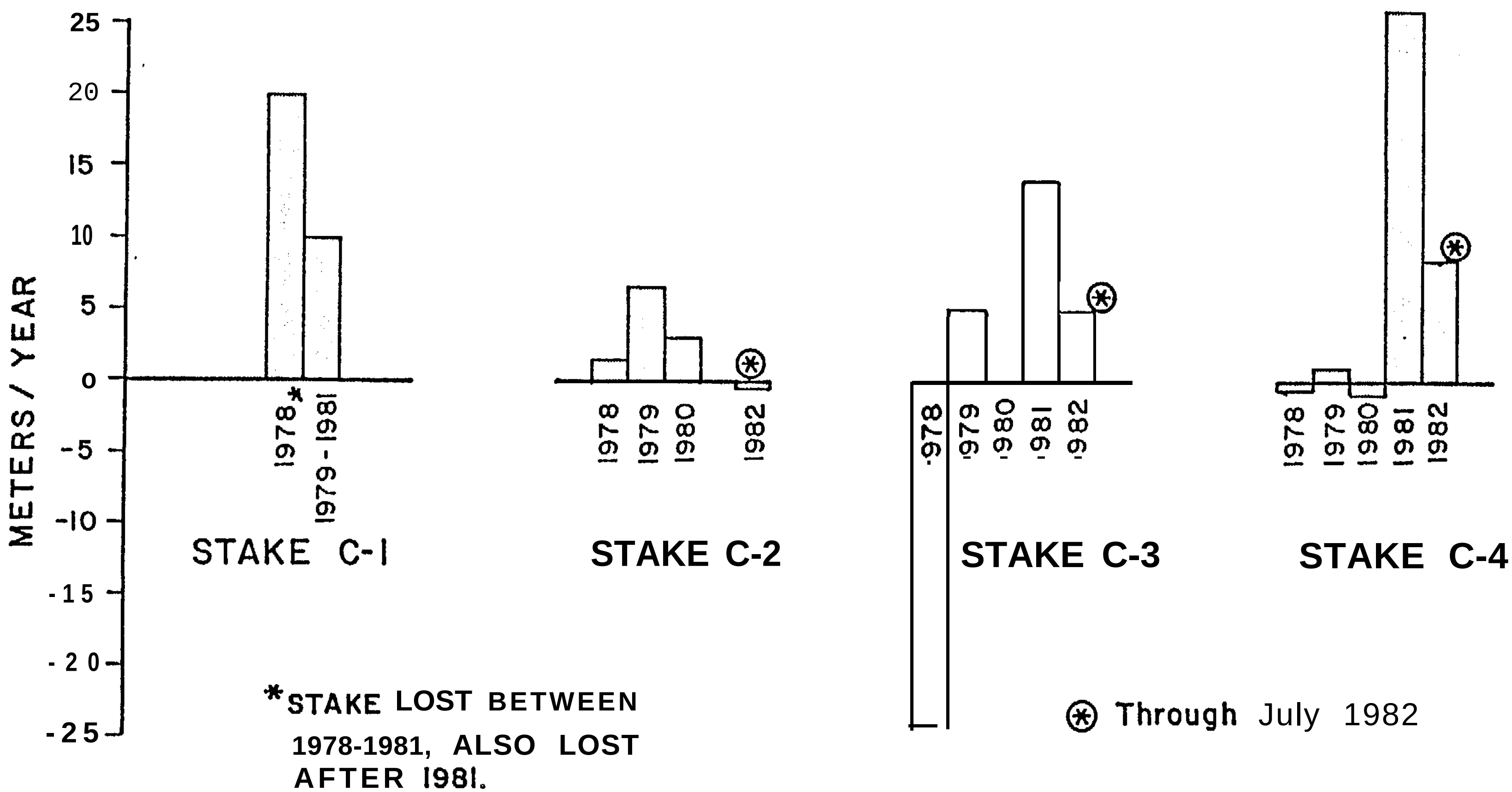

Figure 11: Mt. Redoubt - C-stake emergent velocities

projecting through the glacier. To the east of the rock plug the wave has an eastward velocity component and is actually advancing over bare ground; to the west it appears to move in a NNE direction, perhaps because of the blocking effect of stagnant ice along the west margin of the glacier.

Interpretation. "

The North Glacier on Mt. Redoubt is undergoing an anomalous motion event, herein termed a pulse, in which the ice of the lower glacier is accelerating vertically and horizontally. This event fits Meier and Post's (1969) definition of a glacier surge in that

1. speeds of flow on the glacier are an order of magnitude faster than flow rates at the same location prior to the surge.
2. The event is taking place in a relatively short period of time (e.g. perhaps as little as five years).
3) There appears to be an "ice reservoir" from which ice is being removed (the lower canyon and above) and a receiving area into which ice is moving (the piedmont lobe).

There is no evidence, presently, to indicate whether the North Glacier fits the full criteria of surge-type glaciers since we do not know if it has experienced this sort of event in the past and if it has cyclic behavior, though geomorphic evidence may shed light on this subject.

We don't know when the pulse started. The 1977 aerial photographs show distinct pulse-type crevassing above the rock plug which may be the initial stages of the pulse. Alternately, the events of 1966, with changes in volcanic heating and removal of large quantities of ice by jokulhlaups, along with flooding in and under the glacier might have triggered the event, though no connection is presently known.

The wave has traveled down the piedmont lobe with an average velocity of about 450 meters per year. This speed of propagation is more than three times the speed of the ice itself. The speed of the wave does not appear to have been constant. In 1977-1978 it appears to have been traveling between 600 and 900 meters per year while it was still confined by the lower valley walls of the mountain. After 1979, the speed was considerably slower as the pulse left the narrow canyon and spread out over the piedmont lobe (see Figure 12).

The wave front (as defined by crevassing on the glacier surface) was parabolic in plan view in 1977, but as the front passed the rock plug it appeared to divide into two lobes with the flow west of the plug greater than that east of it. The glacier surface immediately down-glacier from the plug has remained undisturbed. The USGS aerial photos taken in 1954 show ogive-like forms replicating this flow pattern. Extrapolating from the 1954 photos, it appears that the dominant west lobe of the wave will first reach the terminus in the vicinity of stake A-3 and A-4. Although the east lobe has lagged behind the west lobe, and its ice surface is less crevassed, it has actually caused some minor advance along the east margin of the glacier (Figure 12).

The crevassing, which we have used to map the progression of the wave down-glacier, may be caused by a pressure wave moving in advance of the wave of accelerated ice flow, which in turn may reflect better lubrication at the glacier bed. At any given time at the location of the wave front there is a down-glacier segment of ice moving slowly, and an up-glacier segment of ice trying to move more rapidly. The effect is that of a dam. The up-glacier ice tends to “pile up” against the down-glacier segment and then, if there is sufficient room, it begins to flow

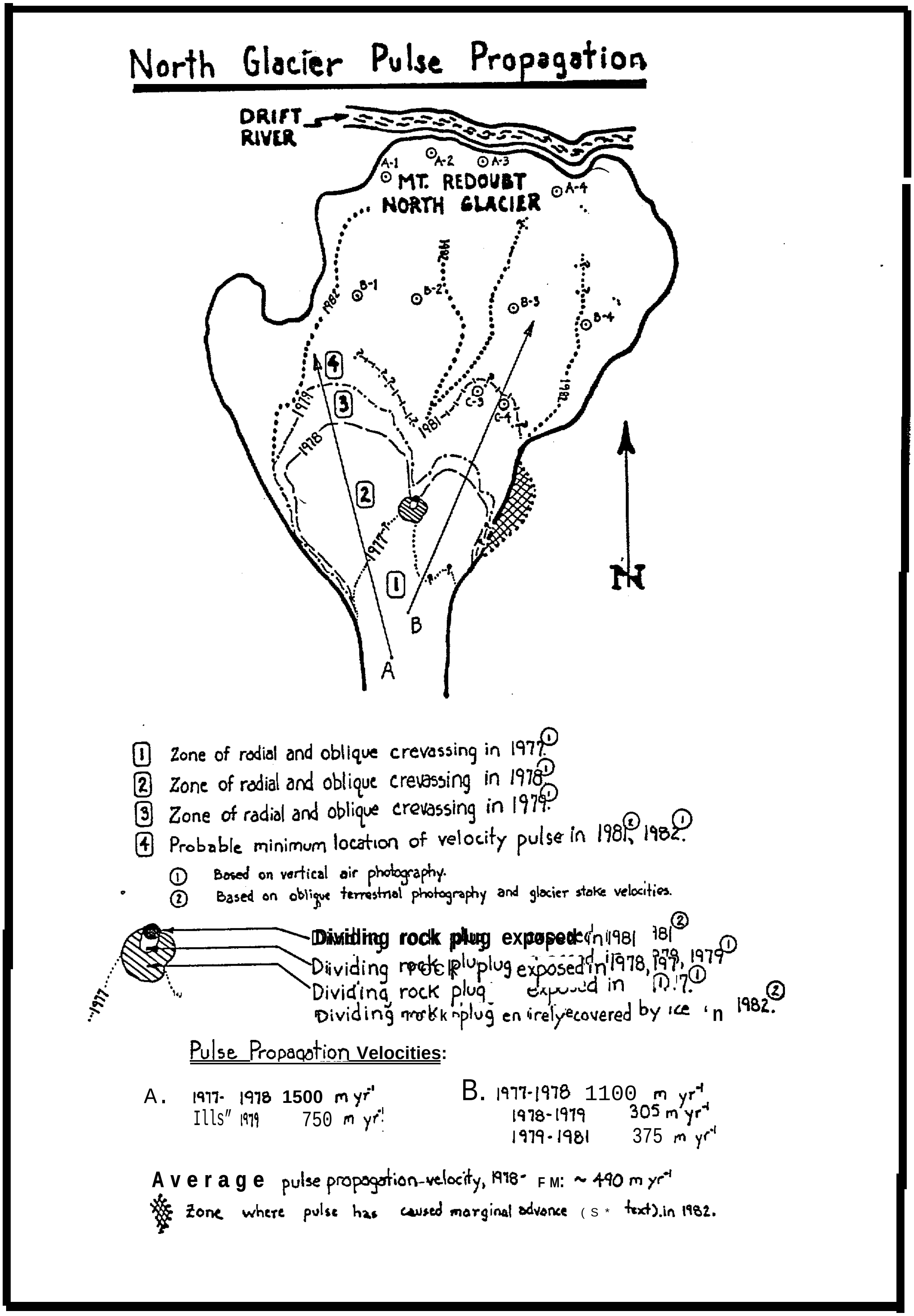

Figure 12: Movement of a pulse of thickening, accelerating ice down the North Glacier, Mt. Redoubt, as defined by aerial photographs

laterally. Because the surface ice has some rigidity, this process takes place down-glacier from the wave front. The net effect is that the ice 'thickens and feels tensile stress perpendicular to its direction of flow. This causes rupture (crevassing) along the direction of flow. This hypothesis seems to fit well with the observed data. We generally first see ice thickening at a stake, followed after a lag of up to a year, by longitudinal (radial where flow is divergent) crevassing and horizontal acceleration.

We have a rough idea of the traveling wave's dimensions, In 1982, the A-line of stakes began showing horizontal and vertical acceleration, while the C-line showed minor signs of deceleration; this suggests that the wave has a wavelength of at least the distance between the two stake lines, or about 1900 meters, The amplitude of the wave is suggested by the total thickening at each stake, which is roughly ten to twenty meters. Using a mean amplitude value of 15 meters, a glacier width of 300 meters, and 1900 meters (the minimum distance) as the wavelength, the volume of ice displaced by the wave is 3.7×10^7 cubic meters.

The nature of the pulse is not well known. Using Glen's Reformational Flow Law for ice, and assuming an ice thickness of 100 meters in the piedmont lobe, a reasonable figure, we find that an ice thickening of about ten meters, with a subsequent increase in surface slope of about 3 to 4 degrees, yields, at maximum, a three-fold velocity increase. This is insufficient to account for the more than ten-fold increases in horizontal velocity seen on the North Glacier. Current glaciological research suggests that this marked increase in velocity is brought about by a decrease in glacier bed friction. This in turn implies that there is more lubricating water at the glacier bed. The propagation of the wave downglacier may actually be the propagation of an increased sub-glacial water film. .

Hypotheses and Speculation

We are entertaining three working hypotheses in our attempts to explain the pulse.

1. The removal of large quantities of ice in the upper valley section of the North Glacier in 1966 may be like removing a bung from a barrel, it allowed ice to spill out of the crater rapidly, in excess of its normal annual flux. This excess has traveled down the North Glacier and is just now arriving at the terminus. This hypothesis is supported by a sequence of photos, taken from 1966 through 1976, which show that the upper valley section, nearly bare of ice after the 1966 flood, was occupied by a reformed glacier by 1974. This new glacier reconnected with the lower valley section by 1975 and moved out onto the existing glacier in a distinct wave bulge. The timing of events supports this hypothesis, for a pulse of ice could travel from the crater to the 1982 pulse location in the elapsed 16.75 years at an average velocity of 480 meters per year, a figure surprisingly close to the 438 meters per year measured for the actual pulse propagation.

2. Volcanic heating or flood waters associated with volcanic events may have radically altered the North Glacier bed conditions and bed friction. With resistance to sliding reduced, accelerated ice velocities would be expected. It is possible to envision this occurring after an eruption in the form of a water film moving from the crater down toward the terminus at the speed of the pulse. Alternately, the process may be an ongoing one which began after the

1966 eruption. In this case, perhaps ice melted by volcanic heat, which prior to 1966 fed an englacial water pocket (source of the jökulhlaups), now percolates down the glacier bed and is accelerating the ice. This leads to the intriguing possibility that jökulhlaups, pulses and volcanic activity are linked on Mt. Redoubt.

3. Flood debris, deposited in 1966, has shut off ablation over much of the ablation area. This has led to a 17 year surplus of ice from the accumulation area, which is moving down as a pulse as discussed earlier.

The question remains whether the North Glacier will experience an advance of its terminus and dam the Drift River. Our models and hypotheses as to the nature and cause of the present anomalous glacier dynamics are much too speculative to allow prediction. Instead, we must rely on the behavior of the glacier measured over the last five years and look for trends. From this, it is clear that the pulse has reached or will reach the terminus shortly. We know that prior to the arrival of the pulse we might see ice thickening, followed shortly by horizontal ice acceleration. We are already beginning to see this along the terminus. Stagnant ice along the west side of the piedmont lobe effectively blocks any lateral spreading in that direction, thus the flux of ice should remain concentrated in the west lobe of flow. This increases the likelihood that enough ice mass for a dam will reach the river. It is increasingly clear that earlier expectations for the pulse to die out when it got to the piedmont lobe were in error; there is a fair likelihood that damming will occur. The size of the lake which could form would depend on the height of the ice dam across the river. We have no way of predicting the height now but it could exceed 60 meters.

CONCLUSIONS

Mt. Redoubt poses a number of real hazards. The volcano has been active five times in the past two hundred years and can be expected to be active in the future. In addition to the normal hazards of eruption, there is a distinct possibility that a jökulhlaups flood on the Drift River will re-occur.

A second flooding hazard is presently in the making. The North Glacier is undergoing an anomalous motion event which may advance the terminus and dam the river. Since the event is already at the terminus, or about to arrive there, it is only a matter of perhaps a year or so before this hazard is realized.

The magnitude of either of these flooding hazards is difficult to predict. Because of the numerous controlling variables, wide variation in flood severity can be expected. It might be unrealistic to assume that previous floods are indicative of the size of future floods. Prudence would suggest a healthy respect for the possible floods the glacier-volcano system could produce.

RECOMMENDATIONS

Full understanding of the processes occurring on Mt. Redoubt requires dealing with the system as a whole. As has been shown in this report, glacier action on the mountain is not independent of volcanic action, and perhaps, the reverse also holds true. Therefore, the recommendations listed below are best combined into research relating to the whole system.

1. SUMMIT CRATER:

a) Ice Mass Flux: The dynamics of the North Glacier require more accumulation data from the summit crater. This could be obtained through snow pits and drilling a core to some 50 meters. Flow velocity measurements of the crater outlet glaciers along with radio-echo sounding profiles throughout the crater and its outlet channels would give the flux exiting the summit crater.

b) Jökulhlaups Hazard: There is a need to investigate whether any water is presently ponded below or within the summit crater. Methods for doing this need to be investigated. Additionally, radio-echo sounding of the crater sub-glacial topography is needed for better understanding of the jökulhlaups release mechanisms.

2. EAST BASIN, UPPER CANYON, LOWER CANYON:

a) Ice Mass Flux: We presently have neither motion data nor accumulation data for these areas. Two snow pits in the East Basin would give the necessary data, along with the summit work, to construct an adequate accumulation gradient for the mountain. This would in turn give us a better idea of total accumulation. Ice velocity in the lower canyon section can be measured using tetrahedral markers, with surveying by electronic distance ranger and theodolite. We have already proposed to measure the ice thickness changes in the lower canyon using photogrammetric mapping from the aerial photos already obtained. If the survey control network is extended farther up the mountain, this mapping can be extended higher to tell us much about the movement of the pulse.

3) PIEDMONT LOBE:

a) Ice Motion: Continued surveying of established motion stakes at more frequent intervals is a must. Future observations in March, 1982, should give us some idea of the over-winter motion. A number of other surveys' over the course of the summer would greatly enhance our knowledge of the acceleration of the ice. A number of survey stations should be established in front of the terminus (where there is sufficient room beside the river) so that any advance can be closely monitored. Aerial photographs need to be obtained again during the summer of **1983.**

4) MISCELLANEOUS':

a) Extent of Ice-Dammed Lake: Geologic work upstream of the Drift River, including soil coring, examination of natural cut-banks and old lake strandlines should be undertaken in order to reconstruct the size of previous 'lakes dammed by the North Glacier. This would then allow some computation of the size of the hazard which could be expected.

b) Flood Hazard Mitigation: There are a number of methods by which the formation of a glacier-dammed lake might be prevented. These include:

1. Keeping a water passage clear with explosives.
2. Keeping the ice dam thinner by removing glacier debris cover and allowing ablation to increase.
3. Building an inverted siphon over the ice dam.

The feasibility of these and other methods needs to be investigated.

APPENDIX I

Listing of Mt. Redoubt Aerial Photos

Date	Type	Notes	Source
1936	Oblique	North & south sides	Bradford Washburn
3/6/53	Oblique	Summit crater	
8/29/54	Vertical	Mapping photos	USGS?
8/25/63	Oblique	North & east sides	Austin Post
8/25/64	Oblique	North, south, east and piedmont lobe	Austin Post
9/3/66	Oblique	North, south and piedmont lobe; shows flood channels	Austin Post
8/22/68	Oblique	Summit Crater	Austin Post
8/26/69	Oblique	Summit Crater	
9/2/70	Oblique	South and NE sides	Austin Post
9/2/70	Vertical	Piedmont and lower canyon	Austin Post
8/74	Oblique	Summit Crater and north side	Hall
7/1/77	Vertical	Entire area	North Pacific Aerial Survey (NPAS)
7/77	Oblique	Various areas	C.Benson/J.Kienle
7/78	Oblique	North side	Peter MacKeith
7/31/78	Vertical	Entire area including Drift River	NPAS
8/22/79	Vertical	Entire area	NPAS
8/79	Oblique	Summit Crater	Peter MacKeith
5/26/81	Oblique	North side and Summit Crater	Matthew Sturm
7/28/82	Oblique	North side	Matthew Sturm
9/23/82	Vertical	Entire area	NPAS
10/15/82	Oblique	North side	Matthew Sturm

REFERENCES

Beaglehole, J.S., The Journals of Captain James Cook on His Voyages of Discovery III, Cambridge, Cambridge Univ. Press, p. 370, 1967.

Driedger, Caroly, "Effect of Ash Thickness on Snow Ablation", in The 1980 Eruption of Mount St. Helens, Washington USGS Professional Paper 1250, USGS, 757-560, 1981.

Grewingk, Verhandlungen der Russisch-Kaiserlichen Mineralogischen Ge'sell-schaft zu, St. Petersburg, Zweite Serie, Funfter Band, 1870.

Meir, Mark and Austin Post, "What are Glacier Surges", Canadian Journal of Earth Sciences, 6, 4, Part 2, 807-817, 1969.

Panuska, Aimee, The 1902 and 1933 Eruptions of Redoubt Volcano, Unpublished Paper, Univ. of Alaska, Geoscience Dept., 1978.

Post, Austin and Laurence R. Mayo, "Glacier Dammed Lakes and Outburst Floods in Alaska", Hydrologic Investigations Atlas HA-455, U.S. Geological Survey, 1971.

Riehle, James R., Juergen Kienle and Karen S. Emmel, Lahars in Crescent River Valley, Lower Cook Inlet, Alaska, Alaska Geological and Geophysical Surveys, Geologic Report 53, 1981.

Small, Harriet, Mt. Redoubt Eruptions: A Chronology, Unpublished paper, Univ. of Alaska, Geoscience Dept., 1978.

Wilson, C.R. and R.B. Forbes, Infrasonic Waves from Alaskan Volcanic Eruptions: J. Geophys. Res., 74, 18, 4511-4522, 1969.

Wilson, C.R., S. Nichparenko and R.B. Forbes, Evidence for Two Sound Channels in the Polar Atmosphere from Infrasonic Observations of the Eruption of an Alaskan Volcano, Nature, 211, 163-165, 1966.